POTENTIALS OF GLOBAL POSITIONING SYSTEM FOR METEOROLOGY IN LOW-LATITUDE REGIONS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
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Dedicated to

My precious parents,
Ab Latip B Buyong and Jamaaiah Bt Ismail

My loving wife,
Sharifah Ainul Mardhiah Bt Syed Shahar

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ABSTRACT

Water vapor plays an important role in weather forecasting and climate monitoring, particularly in low-latitude regions which contain large amount and inhomogeneous water vapor. The Global Positioning System (GPS) has the ability to provide observations of water vapor continuously and more frequently for wide areas with high accuracy in all weather conditions. The GPS continuously operating reference station (CORS) data processing allows the estimation of zenith path delay (ZPD) from the GPS CORS network and will be further processed into integrated water vapor (IWV) using surface meteorological data. This research aims to study the potential of using the GPS for meteorology applications in low-latitude regions. In this study, the ZPD values from Australia and Peninsular Malaysia were derived in order to investigate the variability of water vapor in these two regions. Besides, the continuous result of the GPS-derived IWV assessment with radiosonde-derived IWV for one year data in Peninsular Malaysia are also discussed. Based on the analysis of the ZPD from the two regions, the water vapor is high and its change is rapid in Peninsular Malaysia. The quality of the ZPD obtained was compared to the International GNSS Service (IGS) troposphere products; the root mean square (RMS) errors of the GPS-derived ZPD are in the range of 4 to 12 mm. Meanwhile, the large amount of IWV and its variability in Peninsular Malaysia shows a close relationship with the monsoon seasons in this area. Four GPS stations close to radiosonde stations were assessed; the RMS errors of the GPS-derived IWV are 3.447 kg/m^2, 3.786 kg/m^2, 4.122 kg/m^2 and 4.253kg/m^2 and their linear correlation coefficients are 0.877, 0.797, 0.851 and 0.849, respectively. This strong correlation shows that there is potential to develop a real-time GPS IWV system in Peninsular Malaysia. This study also reports on an initial development of real-time GPS IWV system known as UTM GPS-MET which was designed starting from data collection, data processing and results dissemination. Several tests on this initial system found that the total time delay in UTM GPS-MET from data collection until the result dissemination is within one minute and 37 seconds, the time period which can support the real-time GPS IWV application.

ABSTRAK

Wap air memainkan peranan sangat penting dalam peramalan cuaca dan pemantauan iklim, terutama di kawasan latitud rendah yang mengandungi wap air yang tinggi dan tidak seragam. Sistem Penentududukan Global (GPS) mempunyai keupayaan mencerap wap air secara berterusan dengan lebih kerap bagi kawasan yang luas dengan ketepatan yang tinggi dalam semua keadaan cuaca. Pemprosesan data GPS dari stesen rujukan yang beroperasi secara terus (CORS) membolehkan penganggaran lewatan laluan zenith (ZPD) dari rangkaian GPS CORS seterusnya diproses untuk mendapatkan integrasi kandungan wap air (IWV) menggunakan data meteorologi permukaan. Penyelidikan ini bertujuan mengkaji potensi penggunaan GPS untuk aplikasi meteorologi di kawasan latitud rendah. Dalam kajian ini, nilai ZPD dari Australia dan Semenanjung Malaysia telah diperoleh bagi mengkaji perubahan wap air di kedua-dua rantau ini. Selain itu, hasil penilaian GPS IWV dengan belon kaji cuaca IWV secara berterusan bagi tempoh setahun di Semenanjung Malaysia turut dibincangkan. Berdasarkan analisis ZPD dari kedua-dua rantau ini, wap air adalah tinggi dan perubahannya adalah pantas di Semenanjung Malaysia. Kualiti ZPD yang diperoleh telah dibandingkan dengan ZPD daripada International GNSS Service (IGS); ralat punca min kuasa dua (RMS) untuk GPS ZPD yang diperoleh adalah dalam lingkungan 4 mm hingga 12 mm. Sementara itu, jumlah IWV yang tinggi serta perubahannya di Semenanjung Malaysia telah menunjukkan hubungan yang rapat dengan musim monsun di kawasan ini. Empat stesen GPS yang berdekatan dengan stesen belon kaji cuaca telah dinilai; ralat RMS untuk GPS IWV yang diperoleh adalah 3.447 kg/m^2, 3.786 kg/m^2, 4.122 kg/m^2 dan 4.253 kg/m^2 dengan pekali korelasi linear masing-masing ialah 0.877, 0.797, 0.851 dan 0.849. Korelasi yang tinggi ini menunjukkan terdapat potensi untuk membangunkan sistem GPS IWV dalam masa hakiki di Semenanjung Malaysia. Kajian ini juga melaporkan pembangunan awalan sistem GPS IWV dalam masa hakiki dikenali sebagai sistem UTM GPS-MET yang direkabentuk bermula dari pengumpulan data, pemprosesan data dan penyebaran hasil. Beberapa ujian ke atas sistem awalan ini mendapati bahawa jumlah lewatan masa sistem UTM GPS-MET dari proses pengumpulan data sehingga penyebaran hasil adalah dalam jangka masa 1 minit 37 saat, iaitu tempoh masa yang dapat menyokong aplikasi GPS IWV dalam masa hakiki.

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LIST OF ABBREVIATIONS

ARGN	-	Australian Regional GNSS Network
BINEX	-	Binary Independent Exchange
BKG	-	Federal Agency for Cartography and Geodesy
C/A-code	-	Coarse acquisition code
CL	-	Civilian long
CM	-	Civilian moderate
CODE	-	Center for Orbit Determination in European
CORS	-	Continuously operating reference station
DD	-	Double difference
DoD	-	Department of Defense
DSMM	-	Department of Survey and Mapping Malaysia
DWD	-	German Weather Service
EMR	-	Electromagnetic radiation
EPOS	-	Earth parameter and orbit parameter software
FTP	-	File transfer protocol
GASP	-	GPS Atmosphere Sounding Project
GEONET	-	GPS Earth Observation NETwork
GFZ	-	GeoForschungsZentrum
GIMs	-	Global ionosphere maps
GIPSY	-	GNSS-inferred positioning system and orbit analysis simulation

		software
GPS	-	Global Positioning System
GSI	-	Geographical Survey Institute
HTML	-	Hypertext markup language
IDD	-	Internet data distribution
IF	-	Ionosphere-free
IGS	-	International GNSS Service
IP-VPN	-	Internet protocol virtual private network
IWV	-	Integrated water vapor
JMA	-	Japan Meteorological Agency
JPL	-	Jet Propulsion Laboratory
KKPG	-	Kolej Komuniti Pasir Gudang
LAMBDA	-	Least-squares AMBiguity Decorrelation Adjusment
LC	-	Linear combination
LEO	-	Low-Earth-orbit
LM	-	Local model
MET	-	Meteorology
MHZ	-	Megahertz
MMD	-	Malaysia Meteorological Department
MRI	-	Meteorological Research Institute
MSL	-	Mean sea level
MyRTKnet	-	Malaysia Real-Time Kinematic GNSS Network
NEQ	-	Normal Equation
NMF	-	Niell mapping function
NOAA	-	National Oceanic and Atmospheric Administration
NTRIP	-	Networked transport of RTCM via internet protocol
NWM	-	Numerical weather model
NWP	-	Numerical weather prediction
P-code	-	Precision code
PCV	-	Phase centre variations
PPP	-	Precise point positioning

PRN	-	Pseudo-Random Noise
PTP	-	Port of Tanjung Pelepas
PWV	-	Precipitable water vapor
QIF	-	Quasi-ionosphere-free
R&D	-	Research and development
RAM	-	Random access memory
RF	-	Radio frequency
RINEX	-	Receiver INdependent EXchange
RMS	-	Root mean square
RO	-	Radio occultation
SAPOS	-	German Land Surveying Agencies
SPD	-	Slant path delay
STD	-	Standard deviation
TEC	-	Total electron content
UNAVCO	-	University NAVSTAR Consortium
UPS	-	Uninterruptible power supply
US	-	United State
UTM	-	Universiti Teknologi Malaysia
WVR	-	Water vapor radiometer
ZHD	-	Zenith hydrostatic delay
ZPD	-	Zenith path delay
ZTD	-	Zenith total delay
ZWD	-	Zenith wet delay

LIST OF SYMBOLS

P	-	Code range observation
p	-	Geometric satellite-receiver range
c	-	Speed of electromagnetic radiation
dt^s	-	Satellite clock error
dt_R	-	Receiver clock error
d^{ion}	-	Ionospheric delay
d^{trop}	-	Tropospheric delay
dH^s	-	Satellite hardware delay
dH_R	-	Receiver hardware delay
d^{mp}	-	Multipath effect
e	-	Pseudorange measurement noise
L	-	Carrier phase observation
λ	-	Wavelength of corresponding carrier phase
N	-	Unknown 'integer carrier phase ambiguity'
E	-	Carrier phase measurement noise
N_e	-	Electron density
ds	-	Path length
f	-	Frequency
α	-	Arbitrary numbers

β	-	Arbitrary numbers
i	-	Integer number
j	-	Integer number
ϕ	-	Latitude
n	-	Refractive index of the troposphere
N^{trop}	-	Refractivity of the troposphere
d_h^{trop}	-	Dry delay
d_w^{trop}	-	Wet delay
M_h	-	Hydrostatic mapping function
M_w	-	Wet mapping function
E	-	Satellite Elevation angle
h	-	Station height
$a_{hydro}, b_{hydro}, c_{hydro}$	-	Hydrostatic coefficient
$a_{wet}, b_{wet}, c_{wet}$	-	Wet coefficient
a_{ht}, b_{ht}, c_{ht}	-	Height correction constants
T	-	Temperature
P_r	-	Pressure
e_w	-	Water vapor pressure
ρ_w	-	Density of atmospheric water vapor
P_s	-	Surface pressure
θ	-	Latitudinal variation of the gravitational acceleration
k_3	-	Constant value
k'_2	-	Constant value
R_v	-	Gas constant
T_m	-	Weighted mean temperature
T_s	-	Surface temperature
ρ_w	-	Density of liquid water

w	-	Weight
z	-	Zenith angle
P_{MSL}	-	Pressure at MSL
P_{SM}	-	Pressure at a meteorological station
H_M	-	Height above MSL at a meteorological station
T_{MSL}	-	Temperature at MSL
P_{SM}	-	Temperature at a meteorological station
P_{GPS}	-	Pressure at a GPS station
T_{GPS}	-	Temperature at a GPS station
H_G	-	Height above MSL in meters at a GPS station
P_T	-	Pressure at the top of troposphere
q	-	Specific humidity
g_s	-	Gravity of Earth
T_d	-	Dew-point temperature
L1	-	GPS frequency of 1575.42 MHz
L1C	-	GPS frequency of 1575.42 MHz
L2	-	GPS frequency of 1227.60 MHz
L2C	-	GPS frequency of 1227.60 MHz
L3	-	Ionosphere-free linear combination
L5	-	GPS frequency of 1176.45 MHz
t	-	Time
ZPD_{est}	-	Estimated ZPD
ZPD_{IGS}	-	IGS ZPD

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CHAPTER 1

INTRODUCTION

1.1 Atmospheric Water Vapor: Distribution & Measurement Techniques

Water vapor plays an important role in meteorological processes that act over a wide range of spatial and temporal scales of the Earth water cycle or hydrological cycle. In the hydrological cycle, the movement of water vapor from the sea and land to the atmosphere leads to the formation of clouds. From cloud, precipitation such as rain or snow falls back to the Earth's surface, thus supplying rivers which flow back to the sea (Moran *et al*., 1997). The water vapor is a dominant greenhouse gases in the atmosphere. Greenhouse gases absorb or trap more of the heat energy from sunlight that escapes from the Earth. Hence, it creates more warming to the Earth's surface. This is known as the Greenhouse Effect.

The Earth's weather and climate is heavily influenced by the amount of water vapor in the lower part of the (neutral) atmosphere known as the troposphere. Nearly all atmospheric water vapor is concentrated in the troposphere (Buchdahl and Hare, 2000). Approximately, more than 90% of the water vapor is contained in the lower 5 km and less than 6% of the water vapor is contained above 5 km of the troposphere, and only less than 1% is in the stratosphere (Tao, 2008). The global distribution of water vapor has a significant latitudinal dependence (see Figure 1.1). Large amount of water vapor is concentrated in low-latitude region (red areas) and it decreases towards high latitude region (blue areas). This is due to low-latitude region that gains more solar radiation, especially in the tropical area, which causes the temperature increases compared to the high latitude region. Therefore, it often gets heavy rainfall. The minimum annual precipitation is normally around 2,000 mm and the relative humidity frequently exceeds 70%.

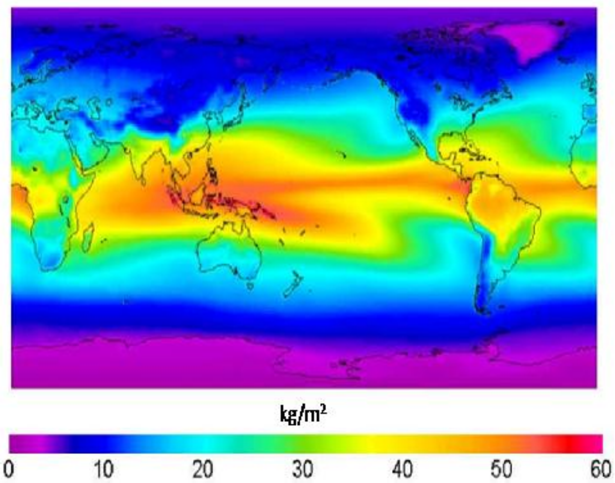

Figure 1.1: The global distribution of water vapor derived from the NASA water vapor project
(Source: CIRA's, 2011).

Malaysia is located in the low-latitude region. As a tropical country, the area has a large amount of water vapor in the atmosphere. Moreover, the high amount (and variation) of atmospheric water vapor in Malaysia shows a close relationship with its unique monsoon seasons (Musa, 2007). The monsoons often bring large amount of rainfall over a very short period of time. This condition sometimes leads to flash flooding (see Figure 1.2) in the eastern part of the Malaysian Peninsula and west coast of Sabah and Sarawak especially during the Northeast monsoon. The flash flood produces a lot of damage to public and private goods, infrastructure, agriculture, environmental, industry and also sometimes loss of lives.

In contrast, abundant water and sunlight in Malaysia help the tropical ecosystem to hold the largest biodiversity of all biomes which is an important basis for socio-economic development, natural resource management and conservation. In fact, the understanding of the dynamics of the tropical atmospheric water vapor directly benefits to the study of global warming, tropical epidemiology, energy and water safety, tropical medicine, tropical rainforest biodiversity and food production. Malaysian should take a leading role in research and development (R&D), locally and internationally, to sustain the biodiversity and its tropical properties with much of concern on the dynamics of the atmospheric water vapor.

Figure 1.2: An example of major flood in Kelantan
(Source: BERNAMA, 2012)

Water Vapor Measurement Techniques

Conventional observing techniques for the measurement of the vertical and horizontal distribution of water vapor can be categorized as: (i) in-situ measurements, *i.e.,* radiosondes, (ii) remote sensing from the ground, *i.e.,* ground-based upward looking radiometry, and (iii) remote sensing from space, *i.e.,* satellite-based downward looking radiometry (Bevis *et al.,* 1992).

Radiosondes are instruments to measure pressure, temperature, dew point temperature as well as wind speed and direction through a profile of the Earth's atmosphere up to the altitudes of approximately 30 km (see Figure 1.3). These instruments are usually carried into the atmosphere by a balloon filled with helium or hydrogen (Agustan, 2004). A radio transmitter attached with the instruments package transmits the observed meteorological data to the ground station by radio signal. Although, radiosonde provides high vertical resolution profiles of water vapor, but it has limited in terms of spatial coverage, expensive to operate and is only launched twice-daily (Geurova, 2003). A further physical limitation of the radiosonde is the accuracy of the humidity sensor, which suffers from three types of errors: systematic observational error, spatial and temporal inhomogeneity, and diurnal and spatial sampling errors (Wang and Zhang, 2008). Although the radiosonde has limitations, it is still one of the major meteorological measurement techniques worldwide (Dodson *et al.,* 2001).

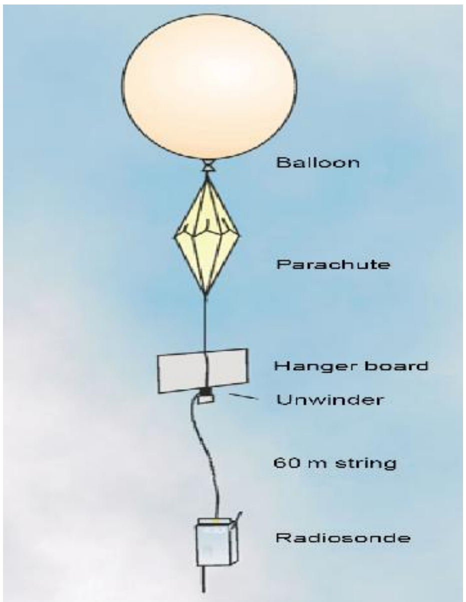

Figure 1.3: Radiosondes instruments
(Source: Dabberdt *et al.,* 2003)

The ground-based, upward-looking water vapor radiometer (WVR) provides measurement of integrated water vapor (IWV) along a given line of sight through the Earth's atmosphere (see Figure 1.4). It measures the sky emission at two frequencies.

One channel is at 23.8 GHz and the other is at 31.4 GHz. The sky emission is caused by the amounts of water vapor, liquid water and oxygen in the atmosphere. By measuring the sky brightness temperature which depends on the surface temperature, sky temperature and surface dielectric constant (index of refraction), water vapor can be observed (Agustan, 2004). The ground-based WVR provides high temporal resolution of water vapor, but low in spatial resolution, requires frequent calibration, affected by rain and clouds with additional constraints on high instrument cost (Geurova, 2003).

Figure 1.4: Water vapor radiometer
(Source: http://sky.ccny.cuny.edu/wc/radiometer2.html)

The satellite-based, downward-looking WVR measures microwave emissions from the atmosphere and underlying Earth's surface (see Figure 1.5). The recovery of IWV by downward-looking WVR is greatly affected by large variability in the surface brightness temperature and the results are reliable only in cloud-free regions. For this reason, satellite-based radiometry tends to be more reliable over the oceans than over land regions. Moreover, although the satellite-based WVR provides good spatial coverage, it exhibits poor temporal resolution (Agustan, 2004).

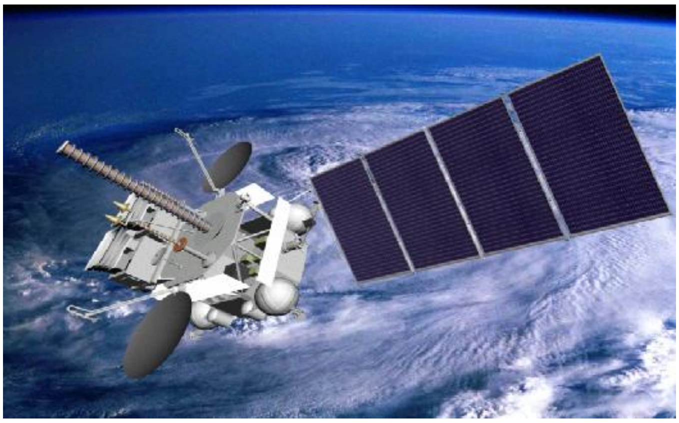

Figure 1.5: Electro-L weather satellite
(Source: Tiger, 2011)

Opportunities for atmospheric sensing using GPS technique

The Global Positioning System (GPS) signals travelling from satellite to receiver propagate through the troposphere layer. The signals experience a propagation delay due to the amount of a mixture dry gases and water vapor in the troposphere layer. This increases the time of delay for the signal when it travels through this layer. The effects of the time delay due to the troposphere are called tropospheric refraction, tropospheric path delay or simply tropospheric delay (Hofmann-Wellenhof *et al.,* 2001). The total tropospheric delay in the GPS signal is known as slant path delay, or in zenith direction is known as tropospheric zenith total delay (ZTD) or tropospheric zenith path delay (ZPD). The ZPD can be estimated from a network of GPS continuously operating reference station (CORS), resulting in a time series of ZPD at each station. Together with surface pressure and temperature data at the location of the GPS CORS, the IWV or equivalently precipitable water vapor (PWV) can be inferred, and it is realized as a useful quantity for meteorological applications (Bevis *et al.*, 1992). This technique of sensing water vapor in the atmosphere often referred as 'GPS meteorology'.

Many studies have been carried out to prove the accuracy of the GPS meteorology compared to the conventional observing techniques. Rocken *et al.* (1995) has demonstrated the proof of concept of GPS meteorology in a GPS/STORM project in

United States (US). They found that the GPS-derived IWV and WVR-derived IWV exhibit the same level of accuracy with RMS of 1 to 2 kg/m^2. Tregoning *et al.* (1998) further demonstrated the IWV estimates using GPS, radiosonde and WVR in Australia. Based on two months of data processing, they found that the RMS of GPS and radiosonde, also the GPS and WVR estimates of IWV are 1.52 kg/m^2 and 1.42 kg/m^2, respectively. Smith *et al.* (2000) showed that the potential use of real-time GPS IWV estimates in numerical weather prediction (NWP) model in order to improve the accuracy of short term precipitation forecasts. Jin and Luo (2009) looked at the long term (13 years) GPS IWV estimates using globally distributed 155 IGS stations to investigate water vapor for climate study. They found that GPS IWV changes with seasonal cycles, annual and diurnal (24 hours) variations.

1.2 Problem Statement

Water vapor is very important in operational weather forecasting and climate monitoring. They are severely limited to do so by the lacking of accurate, dense and continuous observation of water vapor in the atmosphere (Wolfe and Gutman, 2000). As being mentioned, conventional water vapor observing techniques are radiosondes, WVR and weather satellites. The three techniques have several drawbacks as the following;

- Radiosondes measurement are limited in terms of spatial coverage, expensive to operate in terms of material and labour, and are only launched twice-daily.

- WVR are affected by rain and clouds, and they present very low spatial resolution of water vapor due to additional constraint of high instrument cost.

- Weather satellites have limited over the land because of the variable surface brightness temperature and also have limited temporal resolution because they must rotate in their own orbit with a fixed time frame.

GPS can be utilized as a tool to complement the limitations of the three existing techniques described above. The GPS provides a better spatial-temporal resolution, low cost system, global coverage and all weather condition (not affected by rain and clouds).

Since 1990's, many researches around the world especially in the mid-latitude and near tropic areas have already utilized the applications of the GPS CORS to support many meteorological activities for example in the US, Japan and Europe (Haan, 2006). Aside from the above efforts, only little study was conducted in the low-latitude areas. This could be explained by the lacking of GPS CORS infrastructures and non-existing of surface meteorological sensors at the GPS stations in this area. This situation is rather unfortunate due to the wide range of spatial and temporal conditions of the Earth atmospheric water vapor happens in the low-latitude areas.

Many studies were reported that the variability of the estimated IWV between GPS and WVR ranges from 1 to 2 kg/m^2 (Rocken *et al.,* 1995; Tregoning *et al.,* 1998). However, these studies were conducted at the mid- or high-latitude region where the atmosphere has a water vapor burden smaller than 20 kg/m^2 on the average. Currently, only few studies have taken advantage to investigate the accuracy of GPS-derived IWV in low-latitude region. Therefore, further study on the accuracy of the GPS-derived IWV in low-latitude region needs to be conducted.

The establishment of a real-time GPS IWV system can be used to augment the operational weather monitoring and forecasting. The scientific challenges of a real-time GPS IWV system require GPS observation, orbit correction and surface meteorological data to be available with a nominal latency of several minutes. Furthermore, the large amount of GPS observation data needs to be processed as fast as possible but to maintain high quality of the GPS IWV is difficult. These processes are difficult to balance in GPS data processing as an increasing number of GPS stations or higher quality of IWV solution inherently takes longer time to process. Therefore, a study is required to tackle these challenges in the development of a real-time GPS IWV system.

1.3 Research Objectives

The main aim of this research is to investigate the potential use of GPS meteorology in the low-latitude region.

In order to support the aim, there are three main objectives as follows:

1. ***To estimate the ZPD and IWV from the network of GPS stations***

The ZPD is the direct product from the GPS data processing. The ZPD can be estimated after resolve or model the orbital parameters of the satellites, the receiver positions, ionospheric delays and phase cycle ambiguities. By using the additional surface meteorological data, the estimated ZPD can be further processed into IWV.

2. ***To assess the estimated ZPD and IWV***

Two aspects of the GPS meteorology technique can be assessed. Firstly is on the quality of ZPD estimation and secondly is on the quality of IWV estimates. The quality of ZPD estimation can be assessed in comparison with the IGS ZPD. Besides, in order to prove the quality of GPS IWV estimation, its validity can be determined by using the nearest radiosonde data.

3. ***To design a real-time GPS IWV system***

The design gives end-to-end of the real-time GPS IWV system, including all of the steps from the data acquisition up to the results dissemination. Several experiments and tests can be performed in order to investigate the design of the real-time GPS IWV system.

1.4 Research Scopes

The scope of this research includes:

1. Primarily, the study area focuses on the water vapor distribution in Peninsular Malaysia which is located in the low-latitude region. However, this study is extended to Australia which is located in the mid-latitude region, in order to investigate the horizontal distribution of atmospheric water vapor across the two regions.

2. There are currently two primary techniques for sensing atmospheric water vapor by using GPS; space-based and ground-based techniques. This study concentrates on water vapor estimation using a ground-based technique.

3. The Malaysia Real-Time Kinematic GNSS Network (MyRTKnet) currently consists of 58 GPS stations in Peninsular Malaysia. However, only four of these stations are selected for GPS IWV estimation. This limited selection of GPS stations is due to the availability of meteorological stations adjacent to the GPS stations. In the case of GPS ZPD estimation, the GPS network coverage is extended to include few existing stations from International GNSS Service (IGS) in the low-latitude region.

4. The double difference (DD) ionosphere free linear combination or L3 is used to eliminate the ionopsheric errors and as the fundamental measurements for the GPS ZPD estimation process in this study. These L3 measurements may contain residual errors due

to the imperfect mapping function and multipath model that may be absorbed into the ZPD estimation. However, these residuals errors are not further modelled in the final results since it is beyond the scopes of this study.

5. The GPS network provides an important data source to study water vapor. However, the amount of water vapor cannot be directly derived and evaluated from the GPS network observations without collocated meteorological data. Therefore, it is necessary to take advantages of meteorological data from the existing weather stations closely located to the corresponding individual GPS stations.

6. This study also covers the design and initial development of real-time GPS IWV estimation system. However, due to the lack of the real-time surface meteorological and the real-time GPS data in Peninsular Malaysia (*i.e.,* MyRTKnet), the system can only simulate real-time ZPD computation. This simulation makes use of three GPS CORS distributed over the metro-area of Iskandar Malaysia, known as ISKANDARnet GPS network, as a test-bed for the system. In addition, few IGS stations in South-East Asia, India and Australia were also included to the simulation process.

1.5 Significant of Research

The significant of this research can be summarized as follows:

1. It is a special interest of positioning communities and meteorologist to explore the benefits of GPS meteorology. The ability of GPS of estimating the amount of water vapor in the atmosphere will help to investigate a range of questions about the rainfall and monsoon seasons in Peninsular Malaysia.

2. The initial goal of GPS CORS MyRTKnet and ISKANDARnet is for positioning and geodetic applications. However, this research extends the applications of these CORS infrastructures to be used as a water vapor observation system.

3. This study has developed procedures to allow the estimation of GPS IWV in Peninsular Malaysia by using surface meteorological data collected adjacent to the GPS stations. This study also demonstrates the feasibility of ground-based GPS network and interpolated surface meteorological data for GPS IWV estimation process.

4. This study indicates that GPS has a potential to complement existing water vapor observation techniques in Peninsular Malaysia. A knowledge and the existing infrastructures of real-time GPS network can be utilized to augment water vapor observation system and climate study in this area.

5. This study has put an initiative to design and conduct an initial development of real-time GPS IWV in Peninsular Malaysia. The combination of the best strategy of ZPD and IWV estimates obtained from this study could be useful for full implementation of real-time GPS IWV for Peninsular Malaysia in the near future.

1.6 Organization of the Thesis

This thesis is organized into 6 chapters as follows:

Chapter 1 describes about the background, problem statements, objectives, scopes and significances of the study.

Chapter 2 provides fundamental GPS theory and GPS signal propagation delay. The chapter also puts an effort to explain on the concept of GPS meteorology.

Chapter 3 presents the results of the estimated ZPD from MyRTKnet and Australian Regional GNSS Network (ARGN) CORS. This chapter also presents the quality of the estimated ZPD by comparing the results with IGS final ZPD products.

Chapter 4 presents the results of the estimated IWV in Peninsular Malaysia. This chapter also presents the quality of the GPS-derived IWV by comparing it with radiosonde-derived IWV. The relation of GPS IWV with monsoon seasons, rainfall and geographical location of the GPS CORS in Peninsular Malaysia is also discussed.

Chapter 5 starts with some reviews on existing real-time GPS IWV system. Next, the initial design of real-time IWV system in Peninsular Malaysia based on simulation works of ISKANDARnet GPS network as a test-bed is also presented. The simulation of this real-time IWV system includes several tests and data processing strategies.

Chapter 6 summarizes the main findings of this study as well as recommendations for future research works.

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